Microwave diodes

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JUST as the conventional valve suffers from severe limitations when used at microwave frequencies, so does the transistor suffer from similar defects. In the case of the transistor, the trouble lies largely with the mechanism of charge carrier flow across the semiconductor junction. Consider the operation of that ubiquitous device, the diode.

When the junction is forward biased, majority carriers cross the junction depletion layer and enter the opposite side to become minority carriers. They diffuse away from the junction and recombine. The time required for recombination rarely exceeds 10^{-8}s, and if the bias is suddenly reversed before all the charge carriers have recombined, the uncombined carriers will flow back across the junction and form a pulse of current in excess of the normal reverse bias leakage current. This is illustrated in Figure 1.

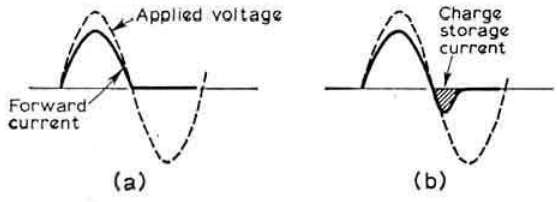

Fig 1. (a) Ideal junction with zero recombination time. (b) Typical junction showing effects of finite recombination time

This delay in recombination has the effect of capacitance and is called the diffusion or storage capacitance. Figure 2(b) shows an equivalent circuit. The junction is represented by a capacitance C_j and a resistance R_j in parallel. The bulk of the semiconductor is represented by the series resistance R_s. In combination with the bulk resistance, the capacitance constitutes the main reason why performance falls off at high frequencies. This dependence upon recombination time is similar in effect to the transit time phenomenon in a valve. Another capacitance effect occurs when the junction is reverse biased. In this case the effect is a useful one, as we shall see in the varactor diode.

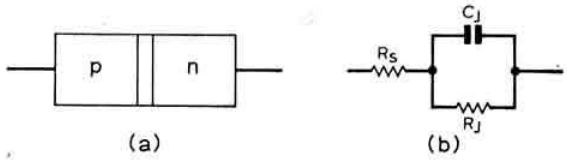

Fig 2. (a) Depletion layer between p-type material and n-type material. (b) Equivalent circuit

The transistor, bipolar and field effect, has still some way to go to reach the level of acceptance that it enjoys at lower frequencies. On the other hand, the diode in one form or another, is well established. The point-contact diode is one such device.

Point-contact diode

The point-contact diode removes some of the disadvantages of the junction diode and permits semiconductors to be used as detectors and mixers up to the highest microwave frequencies. Indeed, the point-contact diode has been used in this way since the earliest days of microwaves. It generally consists of a slab of n-type semiconductor onto which is pressed a pointed wire. This assembly is often mounted in a coaxial structure such as depicted in Fig 3. Since this is a junction between a semiconductor and a metal, the diffusion capacitance is less of a problem than with the junction diode, and the point-contact construction also reduces the reverse bias capacitance.

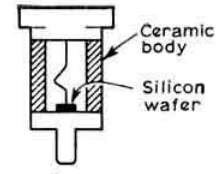

Fig 3. Point contact diode in coaxial mount

Varactor diode

The varactor diode makes use of the reverse bias capacitance referred to previously. When a junction is reversed biased, equal and opposite charges face each other across the depletion layer. This state of affairs is similar to that which obtains in a conventional capacitor, but in the varactor diode the junction capacitance varies with applied voltage, unlike the conventional capacitor in which capacitance is a function only of physical characteristics, size and permittivity. Increasing the reverse bias increases the effective width of the depletion layer and hence decreases the capacitance.

This voltage-variable capacitance is the basis of the parametric amplifier; that is, amplification by changing a parameter of the circuit, in this case, capacitance. Consider the circuit of Fig 4 supplied with a sine wave of constant amplitude. C is a capacitor that can be varied mechanically. When V is maximum the plate separation of the capacitor is increased. The charge on the capacitor, Q, is defined by the relation $Q = CV$, hence if C is decreased then V must

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increase. The plate separation is decreased back to normal when V is zero. Separation is against an attractive force while restoration is against zero force, hence energy is supplied to the circuit.

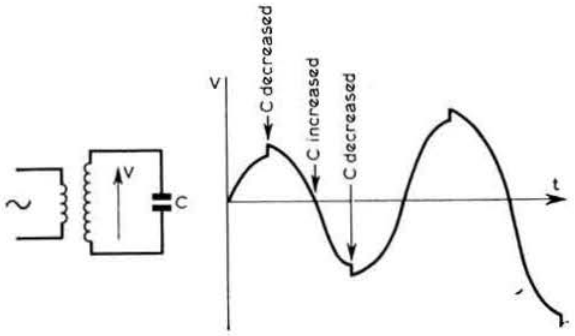

Fig 4. The effect of capacitance change at appropriate moments in the cycle

The energy required to build up the parametric amplification is obtained from the system that varies the capacitance, ie, the "pump". In practice the variable capacitor is a varactor and the pump is an oscillator. Parametric amplification at microwave frequencies is produced in waveguide and coaxial resonant circuits rather than in lumped LC circuits.

The parametric amplifier is a low-noise device since amplification is a function of reactance, and does not involve either reistance or an active device such as a valve or a transistor. Thus thermal (Johnson) noise is low and may be further reduced by cooling the diode. Liquid nitrogen is frequently used for this purpose.

But the usefulness of the varactor diode does not stop here. The reverse bias junction capacitance does not vary linearly with voltage. Capacitance, C, varies as $1/V^n$ where V is the reverse bias voltage, and n is approximately 1/2 for an abrupt junction and 1/3 for a graded junction. This non-linear voltage versus capacitance relationship of the varactor diode makes it a useful harmonic generator and this is the method of operation most used by amateurs.

It is well described in the *VHF-UHF Manual*, as is the step-recovery diode. This latter diode is a varactor in which the reverse current pulse, previously described, is exploited. The impurity gradation or "profile" is such that the uncombined charge carriers form an abrupt, or "step", reverse current that is rich in harmonics, see Fig 5.

Tunnel diode

The tunnel diode is yet another microwave semiconductor. It is an alloy junction in which the impurity level is several thousand times that in a conventional diode. This heavy doping reduces the width of the depletion layer to something of the order of 10 to 100 atom diameters. Electrons can pass through (tunnel) from one side to the other without going through the normal diffusion and recombination processes. This permits very fast response, but the junction area must be kept small in order to reduce junction capacitance which is higher, per unit area, than in normal junction diodes because the junction is narrower.

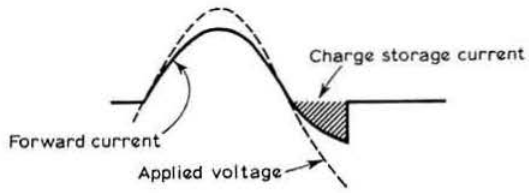

Fig 5. Rapid fall in reverse current is rich in harmonics

A typical tunnel diode characteristic is shown in Fig 6 along with the characteristic of a normal junction diode. The negative resistance region permits the diode to act as an oscillator. The simplicity of the device, (a typical circuit is shown in Fig 7), makes it ideal for use in stripline waveguide, but the device has not achieved the degree of popularity that was expected.

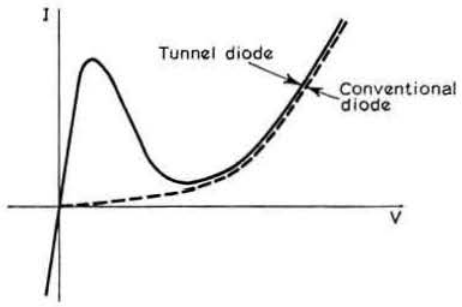

Fig 6. Tunnel diode characteristics

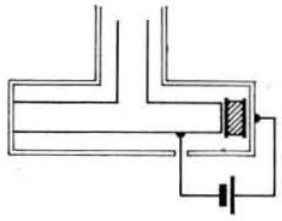

Fig 7. Tunnel diode mounted in coaxial resonator

Hot-carrier diode

Another diode that is becoming increasingly popular as a detector and mixer at microwave frequencies is the hot carrier or Schottky diode. This is a junction formed between a metal and a semiconductor and thus can be considered as the junction version of the point-contact diode. However, the construction is much more controllable. It consists of a planar area between the metal and the semiconductor which results in a low series resistance, lower noise factor, and greater resistance to burn-out.

Operation is based on majority carriers only, so there are no minority carrier storage problems. As the electrons are transported into the metal on forward bias, they acquire energy from the electrical field, and arrive at the metal with more energy than the other free electrons in the metal. Since

they have more kinetic energy they are said to be "hot" compared to the electrons at equilibrium in the metal.

PIN diode

The PIN diode consists of p-type and n-type regions that are separated by an intrinsic region; that is, a region in which there are negligible impurities or charge carriers. Charge carriers from the doped p and n regions have to cross this intrinsic region, and at frequencies below about 100MHz the diode acts as a rectifier. At frequencies above this level, the storage time in the intrinsic region is so great, ie the transit time is so long compared to the period of the signal, that the diode ceases to act as a rectifier and, instead, acts as a linear resistance and conducts in both directions. Its effective resistance is inversely proportional to the amount of charge in the intrinsic region, and this can be controlled by a dc bias. In this way the conductivity can be varied by several orders of magnitude.

PIN diodes are capable of controlling microwave power from microwatts to kilowatts, pulsed or cw operation. A typical PIN diode attenuator is shown in Fig 8. The wave impedance is matched to the diode impedance by the taper. The diode is placed in a position of maximum electric field and absorbs energy from the passing wave in the waveguide. How much energy it absorbs (and dissipates as heat) is determined by the resistance of the PIN diode, which in turn is determined by the bias.

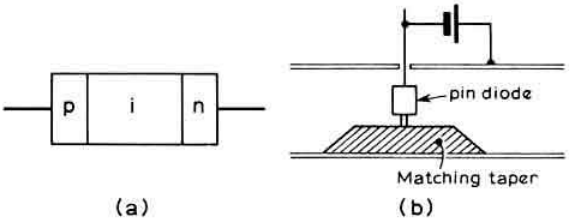

Fig 8. PIN diode mounted in waveguide

IMPATT diode

The IMPATT diode is one of a family of diodes that depends for its operation on two phenomena, avalanche breakdown and transit time. **IMPATT** stands for **IMP**act **A**valanche and **T**ransit **T**ime, and this describes the method of operation. A p-n junction is attached to a drift region, Fig 9(a), and the doping profile (map of impurity concentration) is shown in Fig 9(b). This profile results in a potential gradient that permits avalanche breakdown to occur in a very narrow region at the centre of the depletion layer, and provides a drift region of such low impurity concentration that no further avalanching occurs.

The diode may be operated as an amplifier or as an oscillator. Bias is applied to lift the potential gradient to just below breakdown level, Fig 9(c). In this condition the current that flows is normal reverse bias leakage current. The pulse to be amplified is applied to the diode and this lifts the field across the junction above the breakdown level. Avalanching occurs and large numbers of charge carriers are produced during the time that the field is above the breakdown level. The current pulse that results then travels

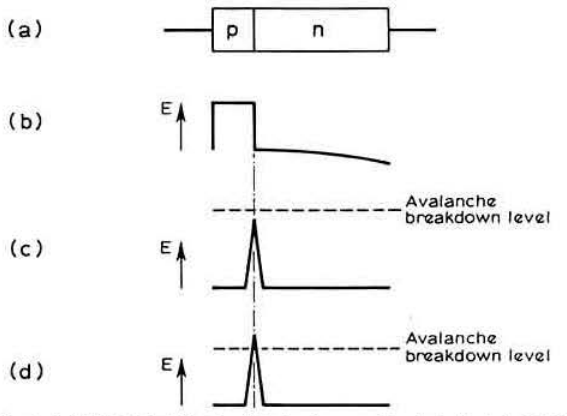

Fig 9. (a) IMPATT diode, (b) doping profile, (c) electric field distribution—diode biased to just below avalanche breakdown, (d) diode raised to just above avalanche breakdown by input signal

down the drift region. When this current pulse reaches the terminal a potential appears across the diode and current flows in the external circuit. Gain of the order of 25dB may be obtained if the period of the input signal is approximately the same as the time required for avalanche plus the delay in the drift region. If some of the output is fed back to the input, to supply the breakdown field, oscillation results.

IMPATT diodes are finding increasing use as amplifiers and oscillators in the microwave region up to 10GHz. A typical amplifier circuit is shown in Fig 10. Since a diode is a two-terminal device, a circulator must be used to separate the output from the input.

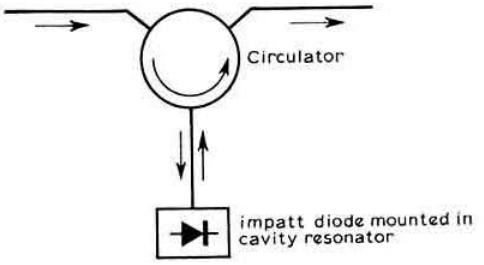

Fig 10. IMPATT diode as an amplifier

Gunn oscillator

All of the semiconductor devices previously mentioned have made use of the interaction at a forward biased or a reverse biased *junction*. Even the point-contact and Schottky diodes are junction devices albeit metal to semiconductor. The Gunn oscillator, on the other hand, makes use of the Gunn Effect, which is a *bulk* phenomenon. It is sometimes termed the Gunn "diode" since there are two connecting terminals, but these serve only to make contact with a specimen of gallium arsenide, see Fig 11.

If an emf is applied to the specimen, the resulting electric field will cause a current to flow as in any resistor. But when the emf is increased to a value that causes the electric field

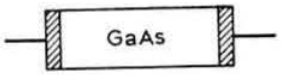

Fig 11. Gunn device

to reach a certain threshold value, some of the electrons will transfer to a higher energy level and become "hot". The effective mass of these hot electrons is increased, which results in a decrease in their mobility. If the field is high enough to cause some of the free electrons in the gallium arsenide to move into this higher energy state, the current through the device will fall since some of the electrons are now less mobile. The current versus field characteristic now has a negative resistance region, Fig 12, region 2.

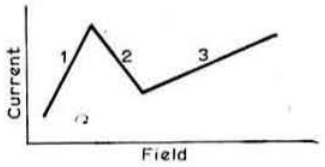

Fig 12. Current versus field characteristic

At this value of field the device is unstable. The field is no longer uniform across the specimen. The reduction in electron mobility has the effect of increased resistance and this in turn causes an increase in field which results in yet more free electrons being formed. But the emf applied across the device is constant, so an increase of field in one part must mean that the field in the remainder is reduced. Thus a cumulative effect builds up a concentration or "domain" of hot electrons in one part of the device. This domain forms at the negative end and then moves across to the positive end. Then, for a brief period, the specimen once again has a uniform electric field until another domain builds up and moves across.

Referring to Fig 12, region 1 is the normal low-field region where electronic mobility is high and resistance is low. Region 3 is the hot electron region resulting from a field above the threshold level. Electron mobility is less than in region 1 and the resistance is therefore higher. In region 2 some of the electrons are in the low energy state and some are in the high energy state. This is the unstable region. The Gunn oscillator is biased to operate in this unstable region by an applied field of between 3 and 12kV/cm. The speed of the domain, as it moves across the specimen, is approximately 10^8 mm/s, and if the gallium arsenide is 10 microns thick, (1 micron is 10^{-3}mm), then the transit time of one domain will be 10^{-10}s, corresponding to a frequency of 10GHz. The current waveform through the device is shown in Fig 13. If the device is placed in a high-Q resonant cavity, these current pulses will excite it into sinusoidal oscillation with an output in the milliwatt region.

Fig 13. Current waveform

A simple microwave transmitter incorporating a Gunn device is illustrated schematically in Fig 14. The device is matched into a length of waveguide that is terminated by a horn antenna, and supplied with a voltage sufficient to cause oscillation as outlined above.

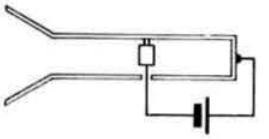

Fig 14. Schematic diagram of simple microwave transmitter incorporating a Gunn device

Summary

This has been a brief review of semiconductor diodes in modern microwave practice. Some of them are well established. Others have yet to come into widespread use. But the fact (a sad fact for the devotee of the valve) is that they have virtually replaced the valve in commercial microwave equipments of powers up to a few watts. Current development is aimed at raising both the frequency at which they will operate and their power handling capability. Some of them are well known to the radio amateur, especially at the lower frequencies. Perhaps they will soon become commonplace with amateurs at microwave frequencies.

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1000	3·6	Cheltenham (SW England)
	145·8	Aberdeen (NNW)
	145·095	Farnham, Surrey (NE)
1015	3·6	Belfast (N. Ireland)
	145·8	Bangor, Co Down (N)
1030	3·6	Derby (N. Midlands)
	145·8	Aberdeen (SW)
	145·89	Bishop Auckland (N)
	145·3	Sutton Coldfield (NW)
1045	145·89	Bishop Auckland (E)
	145·095	Farnham, Surrey (SW)
1100	3·6	Bridlington (NE England)
	3·6	Aberdeen (NE Scotland)
	144·3	Sutton Coldfield (SW)
1130	3·6	Motherwell (S Central Scotland)
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